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Evaluation of a High-Efficiency, Filter-Bank System

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National Institute for Occupational Safety and Health (NIOSH) investigators evaluated filtration efficiencies at three U.S. Postal Service (USPS) facilities. Ventilation and filtration systems (VFSs) had been installed after the 2001 bioterrorist attacks when the USPS unknowingly processed letters laden with B. anthracis *spores. The new VFS units included high-efficiency particulate air (HEPA) filters and were required by USPS contract specifications to provide an overall filtration efficiency of at least 99.97% for particles between 0.3 μm and 3.0 μm. The USPS evaluation involved a modification of methodology used to test total filtration system efficiency in agricultural tractor cab enclosures. The modified sampling strategy not only proved effective for monitoring the total filtration system component of VFS performance but also distinguished between filtration systems performing to the high USPS performance criteria and those needing repair or replacement. The results clearly showed the importance of choosing a pair of optical particle counters that have been closely matched immediately prior to testing. The modified methodology is readily adaptable to any workplace wishing to evaluate air filtration systems, including high-efficiency systems.*

Keywords aerosol, anthrax, bioterrorism, HEPA, high-efficiency filter, optical particle counter

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In October 2001, the mail distribution system of the U.S. Postal Service (USPS) was used for apparent terrorist purposes to distribute *Bacillus anthracis*-laden envelopes. As a direct result of these attacks, a total of 22 cases of anthrax were identified; 11 were confirmed as inhalational anthrax, and 11 (7 confirmed and 4 suspected) were cutaneous.[(1)] Additionally, the Brentwood Mail Facility in Washington, D.C., and the Hamilton Township Mail Facility in New Jersey were closed because of these attacks. Accordingly, the USPS instituted an Emergency Preparedness Plan to limit the effects of any future biological attacks. Measures implemented include deployment of vacuum and filtration technology on automated sorting equipment.[(2)]

In November 2001, the USPS asked the National Institute for Occupational Safety and Health (NIOSH) for technical assistance in evaluating USPS ventilation and filtration systems (VFSs) developed by outside vendors. USPS contract specifications required that a high-efficiency filtration bank system have not only high-efficiency particulate air (HEPA) filters but also provide a total system count efficiency of 99.97% or better against particles ranging from 0.3 μm to 3.0 μm aerodynamic diameter.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) have established well-defined standards and procedures for testing the efficiency of "air-cleaning devices" under controlled laboratory conditions.[(3,4)] ASHRAE standard 52.2-1999 establishes a test procedure for measuring particle size efficiency of general ventilation air-cleaning devices in the laboratory and rates particle size efficiency as a minimum efficiency reporting value (MERV) from 1 to 20, with the higher values being more efficient. This is not an applications standard, so ASHRAE has convened a committee to write guidelines for in situ testing of ventilation filters. This standard does evaluate the leak rate of the test duct by a method similar to that delineated in American National Standards Institute, Inc. (ANSI)/American Society of Mechanical Engineers (ASME) Standard N510.[(5)] Standard N510 addresses field testing of high efficiency air treatment systems for nuclear power plants.

VFS testing for overall filtration efficiency presented a significant challenge. While ASHRAE and other standard-setting bodies have established well-defined standards and procedures for testing the efficiency of air-cleaning devices (i.e., filters), there are no available standards for testing total filtration unit efficiency.[(3,4)] Thus, to meet the strict USPS requirements, NIOSH investigators adapted the procedure found in the American Society of Agricultural Engineers (ASAE) Standard S525.1 for testing total enclosure filtration efficiency on agricultural tractor cabs.[(6)] Although each tested USPS VFS was significantly larger than a filtration system in an agricultural tractor cab, simple inlet modifications to the optical particle counters (OPCs) used for the ASAE procedure allowed successful testing of USPS VFS filtration efficiency. In fact, NIOSH investigators have now used the methodology described in this article to test many USPS ventilation filtration units following the bioterrorist attacks of autumn 2001.

This document details the findings from three separate evaluations of prototype VFSs for the USPS; Survey 1 took place in October 2002 at the USPS Processing and Distribution Center (P&DC) in Merrifield, Virginia, Survey 2 occurred in October 2002 at the USPS P&DC in Dulles, Virginia, and Survey 3 took place in March 2003 at the USPS P&DC in Cleveland, Ohio. These surveys were conducted at the urgent request of the USPS and required a rapid response. The methods in this article describe field tests and should not be considered as a new proposed standard test method or a proposed replacement to any existing standard test method. Publication of the results is intended to demonstrate how this method was rapidly deployed and how OPCs were effectively used to measure the entire filtration component of overall VFS performance.

MATERIALS AND METHODS

Testing Equipment

Testing of the VFSs was intended to determine whether the efficiency of the complete filtration systems met critical performance criteria. Specifically, during normal operation, the entire filtration component of the VFSs was required by USPS contract specification to provide at least 99.97% count efficiency against particles ranging from 0.3 μm to 3.0 μm aerodynamic diameter. The testing method employed two GRIMM model 1.108 portable dust monitors (GRIMM Technologies, Douglasville, Ga.). These OPCs were each equipped with a GRIMM model 1.152 isokinetic sampling probe that sampled parallel to the airstream at a rate of 1.2 L/min. Each isokinetic sampling probe has four inlet nozzles to choose from for sampling airflow velocity. The 3.0 mm nozzle opening was selected because the design airflow velocity for all of the USPS VFS units was 500 ft/min (2.5 m/sec). The 3.0 mm nozzle is designed for the isokinetic sampling of air streams with velocities between 390 and 790 ft/min (2–4 m/sec).

The GRIMM OPC measures number concentration of particles per unit volume of air by light-scattering technology, dependent on a semiconductor-laser as the light source. The OPC determines particle size based upon the amount of light scattered by individual particles that enter the detector. A mirror placed at approximately 90° to the airstream collects the scattered signal and transfers it to a recipient diode. The signal passes to a multichannel size classifier and finally to a pulse height analyzer that classifies the signal according to size into channels and logs the sampling results on a data storage card. Particles are counted in 15 different size channels: 0.30–0.40 μm, 0.40– 0.50 μm, 0.50–0.65 μm, 0.65–0.80 μm, 0.80–1.0 μm, 1.0–1.6 μm, 1.6–2.0 μm, 2.0–3.0 μm, 3.0–4.0 μm, 4.0–5.0 μm, 5.0–7.5 μm, 7.5–10 μm, 10–15 μm, 15–20 μm, and >20 μm. Results are recorded to a data storage card every minute for each size channel. The instrument operates from 4–45°C with a particle concentration range of 1–2,000,000 particle counts per liter. The sensitivity is 1 particle per liter and the instrument reproducibility is quoted as ± 2%.[7]

Mail Processing Equipment

The USPS 010 Culling System (Figures 1 and 2) comprises two conveyor systems that separate the collected mail into letters, flats (magazine size), and parcels. The first system is called the Dual Pass Rough Cull (DPRC) and the second is the Loose Mail Distribution System (LMDS). Hampers of raw mail are loaded into the DPRC. Flats and parcels are separated from the letter mail and sent to the appropriate areas for processing. Letter mail remains on the LMDS where it is sent to the next processing stage, the Advanced Facer Canceller System (AFCS).[8]

The AFCS culls, orients, cancels, scans, and sorts standard-size (5 to 11½ inches [12.7 cm to 29.2 cm] long by 3½ to 6⅛ inches [8.9 cm to 15.6 cm] high) mail pieces. The AFCS culls the mail to remove flats and over-thick (greater than ¼-inch [0.64 cm]) pieces. The mail is then properly oriented for cancellation. Optical character recognition technology reads each mail piece address before sorting and distributing each piece to a numbered bin for further automated processing.

Ventilation and Filtration Equipment

The VFSs for the mail-processing equipment consist of air-handling and filtration units that provide air exhaust at locations of possible contaminant release. The filtration units have three stages of filtration—prefilters, MERV 14 secondary filters, and HEPA filters. The effectiveness of the VFS is enhanced by enclosures on the mail processing equipment. These enclosures and the local exhaust ventilation hoods are fitted around areas having high potential for agitation or compression of mail pieces. Contaminant release from tainted mail pieces has been shown to occur during agitation and compression.[9]

Evaluation Procedures

Matching Pairs of Optical Particle Counters

Because of the high-efficiency levels required by the USPS (≥99.97%), it was important to choose pairs of OPCs where both instruments in the pair provided very similar results. All of the OPCs used on the USPS surveys were calibrated by the manufacturer, and all were certified to be within ± 5% in total particle counts. So, any two calibrated instruments should count the same number of total particles within a ± 5% error, regardless of the individual particle size channel where each particle is counted. That is, one instrument may count a 0.4 μm particle in the 0.30–0.40 μm size channel, whereas another may count that same particle in the 0.40–0.50 μm size channel. Although ± 5% in total particle counts is reasonable for many purposes, closer matching of the instruments was required for testing the USPS VFSs to limit potentially biased results from instrument-to-instrument variability. Prior to the site

FIGURE 1. Part of the ventilation and filtration system installed on a USPS 010 Culling System. The large white filter/fan housing (upper right) was one of the 18,000 cfm (8.5 m^3/sec) units tested as part of this study.

surveys, several identical OPC instruments were tested in the laboratory against ambient aerosol. The particle count results from each OPC were then compared with the others. From the comparisons, two matched pairs of OPCs were selected for VFS testing. Instruments were selected as a matched pair when they met two performance criteria: (1) the two instruments showed total particle counts within $\pm 2.5\%$ in the 0.3 μm to 3.0 μm size range; and (2) the two instruments showed particle

FIGURE 2. Part of the ventilation and filtration system installed on a USPS 010 Culling System. Note the numerous small ducts leading from individual local exhaust ventilation hoods placed above critical areas of the system. All of the small ducts lead back to one of the 18,000 cfm (8.5 m^3/sec) units tested as part of this study.

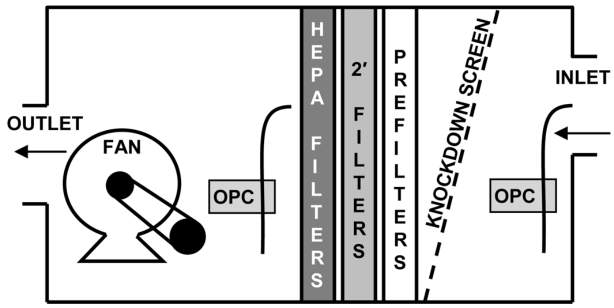


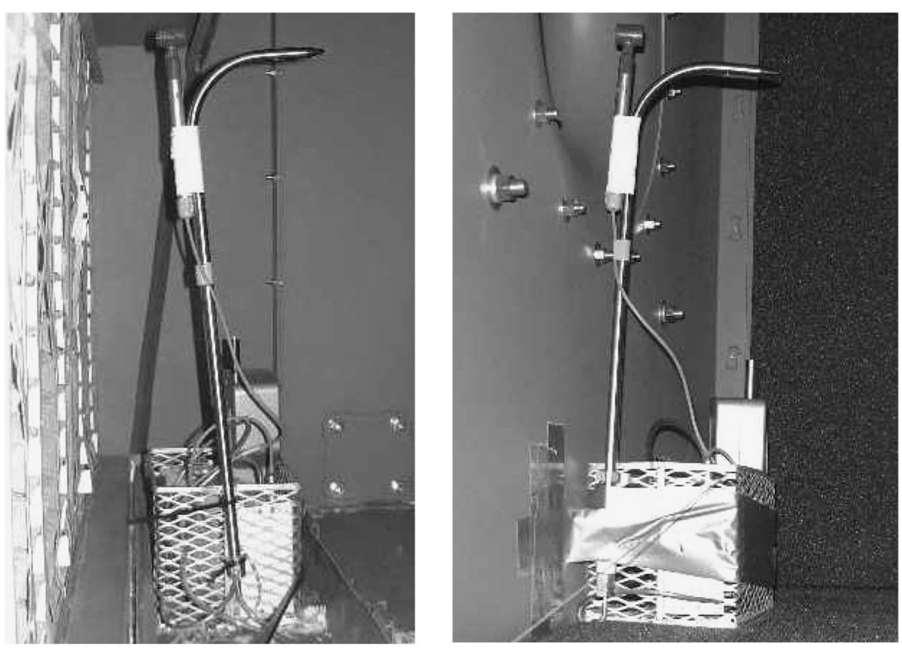
FIGURE 3. Schematic of USPS ventilation and filtration systems showing the locations of the upstream and downstream optical particle counters

counts within ±1.0% in the size channel counting the smallest particles (0.30–0.40 μm).

VFS Testing

To conduct the USPS site surveys of VFS efficiency, the access panels to the knockdown screen chambers and the fan/motor chambers were removed or opened (see Figure 3 for a schematic of filtration system). One of the paired OPCs was placed upstream of the filters to measure particle concentration data, with an isokinetic sampling probe at the center of the filter bank. The probe was placed facing the airstream and as close to the main intake duct as possible (Figure 4A). The second paired OPC was placed downstream of the HEPA filters to measure particle count data, with an isokinetic sampling probe at the center of the filter bank. This probe faced the HEPA filters and was positioned as close to the fan inlet as possible (Figure 4B). The OPC sampling probe was placed in front of the fan to assure that any motor-generated aerosol would not bias the measured downstream particle concentration. In this way, only particles that penetrated the system by (a) filter penetration, (b) leakage around the filters, and/or (c) leakage in the filter housing itself were registered by the OPCs. Once the OPCs were in place, they were turned on and data collection began. The access panels on the VFS housing were replaced and care taken to prevent leakage through the panel seals.

The ambient particles that entered the VFS provided sufficient challenge aerosol for the USPS tests because the mechanical agitation of mail in a P&DC environment produces consistently high levels of background particulate matter. Since the filter housing unit was far downstream of the system inlets, it was assumed that the aerosol was thoroughly mixed and uniform across the sampling area. However, the concentration and the particle size distribution of the ambient aerosol in each P&DC varied dramatically throughout the day depending on the mail processing operations occurring, when they occurred, and in what proximity they occurred to the VFS being tested. To account for any filtration efficiency fluctuations resulting from this variation in the ambient test aerosol, extended testing times were used. The two matched OPCs were operated under normal conditions for at least 45 min; however, the first 15 min of data were ignored to allow for instrument stabilization. At the end



A B

FIGURE 4. Upstream (A) and downstream (B) optical particle counters complete with isokinetic sampling probes

of the testing period, data from both OPCs were downloaded to a portable computer and placed on a spreadsheet for analysis.

Data Analysis

Although the OPCs used for the USPS surveys measured aerosol particle concentration in 15 different size ranges only particle sizes of $\leq 3\ \mu$m were evaluated because the USPS contract acceptance criteria called for a minimum filter system efficiency of 99.97% at a 95% confidence level for the particle size range of 0.3 μm to 3.0 μm. These size ranges all provided sufficient particle count data to achieve statistically significant results. All of the particle count data were below the upper limit of detection for the OPCs (2,000,000 particles per liter), so coincidence or instrument overloading was not an issue.

The OPC data were downloaded for each minute of testing, and efficiency calculations were done for each minute. This provided information on any efficiency fluctuations associated with changes in the ambient aerosol concentration, which could prove useful should a system fail to meet the performance criteria. Therefore, for each particle-size channel up to and including 2.0–3.0 μm, the overall percent filtration efficiency (E) of the VFS for each minute was calculated:

$$E_n = \left[1 - \left(\frac{C_D}{C_U}\right)\right] \times 100 \quad \textbf{(1)}$$

where n is the number for the minute of testing in each particle size range, C_D is the downstream aerosol particle concentration at minute n, and C_U is the upstream aerosol particle concentration at minute n.

Then, an overall mean efficiency ($\bar{E}$) and standard deviation (s) for each particle size range were calculated:[10]

$$\bar{E} = \frac{\sum_1^n E_n}{n} \quad \textbf{(2)}$$

$$s = \sqrt{\frac{\sum_1^n (E - \bar{E})^2}{n - 1}} \quad \textbf{(3)}$$

Finally, the 95% confidence interval around the mean efficiency for each particle size range was calculated as:[10]

$$\bar{E} \pm 1.96 \frac{s}{\sqrt{n}}$$

Because the sample sizes were relatively large, the estimated efficiencies were assumed to follow a normal distribution in the calculation of confidence intervals. This assumption allowed for the rapid calculation of results and reporting to the USPS. After a more thorough analysis of the data following all the USPS surveys, it was found that the data were neither normally nor log-normally distributed. The efficiency data were limited by an upper ceiling value (100% efficiency) that could not be exceeded. This ceiling value produced a negatively skewed distribution with a longer left-hand tail (log-normally distributed data are positively-skewed with a longer right-hand tail). Because of the upper ceiling, mathematical transformations of the efficiency could not serve to normalize the distribution. Thus, the bootstrap method was used to estimate the confidence intervals for the mean of each particle size channel.[11] Bootstrapping (SAS JACKBOOT Macro, SAS Institute, Inc.) produces a confidence interval for a given statistic (the mean in this case) by generating subsamples of the data set with replacement.

For each VFS that met the critical performance criteria of at least 99.97% efficiency, bootstrapping provided confidence intervals around the means for each particle size channel that were tighter than those reported to the USPS after testing. For VFSs that did not meet the efficiency criteria, the bootstrap confidence intervals were typically wider, but they all shifted to higher efficiencies. Thus, for properly performing VFSs, our presentation of 95% confidence intervals (based on a normal distribution) gives a wider confidence interval than the measured efficiencies would actually demand, which has the effect of incorporating a "safety factor" into the results. A safety factor was also incorporated in the results for poorly performing VFSs, as our lower confidence limit was always lower than the lower limit determined through bootstrapping. There was no case where the bootstrapping analysis changed the validity of the results reported to the USPS immediately after testing.

RESULTS AND DISCUSSION

Survey 1—Merrifield, Virginia, Processing and Distribution Center

Three different site surveys of high-efficiency filtration-bank systems were conducted. The first survey, at the Merrifield, Va., P&DC, evaluated two VFS units installed onto the 010 Culling System. The two units (Unit A1 and Unit A2) operated at 18,000 cubic feet per minute (8.5 m^3/sec) and had filter face velocities of approximately 500 ft/min (2.5 m/sec). One of the units is shown in Figure 5. The initial evaluations ran for extended time periods (Unit A1 for 281 min; Unit A2 for 419 min). The data for particle size ranges up to 3.0 μm are shown in Table I. Both units had mean efficiency values and lower 95% confidence limits that all exceeded 99.97 percent. The results of these same two units evaluated 2 days later under identical conditions are also presented in Table I. The retests (Unit A1 for 348 min and Unit A2 for 329 min) produced data consistent with the previous extended runs. All mean efficiency values and lower 95% confidence limits were $\geq$99.97%. Unit A1 and Unit A2 both passed the testing requirement set forth by the USPS, and the results were reproducible employing this sampling technique.

Generally, particles 0.65 μm and larger did not penetrate the filter or otherwise get through the filtration systems (e.g., leaks in the filter housing) installed at the Merrifield P&DC. There were plenty of 0.65 μm and larger (up to 3.0 μm) upstream particles for the efficiency calculation to be valid. There were simply no particles counted downstream in those size ranges, meaning that the filtration units were very effective at capturing particles in those size ranges. This was typical of all VFSs that met the USPS performance criteria, regardless of location.

FIGURE 5. Part of the ventilation and filtration system installed on a USPS 010 Culling System. The large white filter/fan housing suspended above a Loose-Mail Distribution System is one of the 18,000 cfm (8.5 m^3/sec) units tested as part of this study.

Survey 2—Dulles, Virginia, Processing and Distribution Center

The second survey took place at the Dulles, Va., P&DC. The tested VFS consisted of a single 8000 cfm (3.8 m^3/sec) filtration unit (Unit B1; see Figure 6). Again, the filter face velocity was approximately 500 ft/min (2.5 m/sec). In this instance, Unit B1 was designed similarly to the filtration units evaluated in Survey 1, except that the VFS was installed on an AFCS. The

TABLE I. Results from Survey 1—Merrifield P&DC

Particle Size Range	Mean Efficiency (%)	95% Confidence Interval Minimum (%)	95% Confidence Interval Maximum (%)	Mean Efficiency (%)	95% Confidence Interval Minimum (%)	95% Confidence Interval Maximum (%)
	Unit A1			Unit A1 Retest		
0.30–0.40 μm	99.997	99.996	99.999	99.998	99.996	100.000
0.40–0.50 μm	99.995	99.991	100.000	99.996	99.994	99.998
0.50–0.65 μm	99.996	99.990	100.000	99.995	99.990	100.000
0.65–0.80 μm	100.000	—	—	100.000	—	—
0.80–1.0 μm	100.000	—	—	100.000	—	—
1.0–1.6 μm	100.000	—	—	100.000	—	—
1.6–2.0 μm	100.000	—	—	100.000	—	—
2.0–3.0 μm	100.000	—	—	100.000	—	—
	Unit A2			Unit A2 Retest		
0.30–0.40 μm	99.995	99.993	99.997	99.999	99.999	100.000
0.40–0.50 μm	99.991	99.986	99.996	99.999	99.998	100.000
0.50–0.65 μm	99.999	99.996	100.000	100.000	—	—
0.65–0.80 μm	100.000	—	—	100.000	—	—
0.80–1.0 μm	100.000	—	—	100.000	—	—
1.0–1.6 μm	100.000	—	—	100.000	—	—
1.6–2.0 μm	100.000	—	—	100.000	—	—
2.0–3.0 μm	100.000	—	—	100.000	—	—

FIGURE 6. Ventilation and filtration system installed on a USPS Advanced Facer Canceller System (AFCS). The filter/fan housing suspended above the AFCS has a total airflow of 8000 cfm (3.8 m^3/sec).

same basic testing procedure for the filtration units evaluated in Survey 1 was employed here. The test was run for a total of 455 min. As shown in Table II, Unit B1 did not meet the minimum criteria requiring all mean efficiencies and lower 95% confidence limits to be $\geq$99.97%, as mandated by the USPS. The mean efficiency values for the various particle sizes ranged from a low of 98.463% to 99.591%. Because HEPA filter media ($\geq$ 99.97% efficient at 0.3 μm) was employed in the system, it can be assumed that either the media was damaged or a leak site existed, which allowed air to bypass the filters or enter the filter housing downstream of the filters. The fact that high downstream particle counts in the size ranges above 0.65 μm were noticed is further evidence of this. Although this survey impacted the VFS contractor negatively, it proved that the OPC sampling strategy used by NIOSH investigators could, indeed, distinguish between VFS units performing at or above the USPS criteria and units that do not meet the criteria.

TABLE II. Results from Survey 2—Dulles P&DC

Particle Size Range	Mean Efficiency (%)	95% Confidence Interval Minimum (%)	95% Confidence Interval Maximum (%)
		Unit B1	
0.30–0.40 μm	99.251	99.206	99.295
0.40–0.50 μm	99.334	99.219	99.449
0.50–0.65 μm	99.354	99.187	99.521
0.65–0.80 μm	99.460	99.199	99.721
0.80–1.0 μm	99.591	99.350	99.831
1.0–1.6 μm	99.586	99.279	99.893
1.6–2.0 μm	98.463	97.528	99.398
2.0–3.0 μm	99.260	98.839	99.680

Survey 3—Cleveland, Ohio, Processing and Distribution Center

Survey 3 took place at the USPS P&DC in Cleveland, Ohio. The two VFS units evaluated at this location were identical to those tested during Survey 1. Specifically, these units operated at 18,000 cfm (8.5 m^3/sec) and were installed on a 010 Culling System (Figure 5). The data for Unit A3 and Unit A4 are presented in Table III. Unit A3 easily met the minimum performance criteria and the lowest 95% minimum confidence limit was 99.989%, at a particle size of 0.5–0.65 μm. Unit A4 likewise met the performance criteria, having a lowest 95% minimum confidence limit of 99.970% at a particle size of 0.5–0.65 μm. Both runs lasted for approximately 110 min.

During Survey 3, a new, smaller floor version of Unit A (Unit A-Floor) was also evaluated. The Unit A-Floor was installed on a 010 Culling System positioned on the floor, rather than being suspended overhead. Furthermore, it was not as large as the other A units (only 8000 cfm [3.8 m^3/sec] with a filter face velocity of approximately 500 ft/min [2.5 m/sec]), and its placement was vertical with respect to the larger 18,000 cfm (8.5 m^3/sec) units. Unit A-Floor is shown in Figure 7. The one difference that influenced the evaluation of this unit was that it lacked an access door to the downstream filter chamber making it impossible to place the OPC inside the unit. To compensate,

TABLE III. Results from Survey 3—Cleveland P&DC

Particle Size Range	Mean Efficiency (%)	95% Confidence Interval Minimum (%)	95% Confidence Interval Maximum (%)	Mean Efficiency (%)	95% Confidence Interval Minimum (%)	95% Confidence Interval Maximum (%)
	Unit A3			Unit A4		
0.30–0.40 μm	99.998	99.997	99.999	99.990	99.986	99.993
0.40–0.50 μm	99.996	99.992	100.000	99.991	99.984	99.997
0.50–0.65 μm	99.996	99.989	100.000	99.986	99.970	100.000
0.65–0.80 μm	100.000	—	—	100.000	—	—
0.80–1.0 μm	100.000	—	—	100.000	—	—
1.0–1.6 μm	100.000	—	—	100.000	—	—
1.6–2.0 μm	100.000	—	—	100.000	—	—
2.0–3.0 μm	100.000	—	—	100.000	—	—
	Unit A-Floor			Unit A-Floor Re-evaluation		
0.30–0.40 μm	99.714	99.679	99.749	99.989	99.986	99.992
0.40–0.50 μm	99.669	99.603	99.734	99.991	99.987	99.996
0.50–0.65 μm	99.107	98.921	99.294	99.995	99.987	100.000
0.65–0.80 μm	97.941	97.491	98.391	100.000	—	—
0.80–1.0 μm	97.456	96.795	98.118	100.000	—	—
1.0–1.6 μm	96.342	95.165	97.520	100.000	—	—
1.6–2.0 μm	96.156	94.705	97.607	100.000	—	—
2.0–3.0 μm	99.026	98.473	99.579	100.000	—	—

a hole was drilled into the filter housing, on the downstream side of the HEPA filters before the fan. The OPC sampling probe was inserted in the hole and rigidly positioned so that the inlet was oriented in the flow direction. Then, the hole was sealed around the sampling probe by using a generous amount of weatherproofing rope caulk. The results obtained from the evaluation of Unit A-Floor are also presented in Table III. The data clearly show that the unit originally lacked

FIGURE 7. Part of the ventilation and filtration system installed on a USPS 010 Culling System. The white filter/fan housing is the 8000 cfm (3.8 m^3/sec) unit (Unit A-Floor) tested as part of this study.

TABLE IV. GRIMM Pair Testing Results from Survey 3—Cleveland P&DC

Particle Size Range	Mean Efficiency (%)	95% Confidence Interval Minimum (%)	95% Confidence Interval Maximum (%)	Mean Efficiency (%)	95% Confidence Interval Minimum (%)	95% Confidence Interval Maximum (%)	Mean Efficiency (%)	95% Confidence Interval Minimum (%)	95% Confidence Interval Maximum (%)
	OPC Pair #1-Test A			OPC Pair #1-Test B			OPC Pair #1-COMBINED		
0.30–0.40 μm	99.999	99.998	100.000	99.999	99.998	99.999	99.999	99.998	99.999
0.40–0.50 μm	99.997	99.994	100.000	99.997	99.995	99.999	99.997	99.995	99.999
0.50–0.65 μm	99.998	99.993	100.000	99.997	99.992	100.000	99.997	99.994	100.000
0.65–0.80 μm	100.000	—	—	99.989	99.969	100.000	99.995	99.985	100.000
0.80–1.0 μm	100.000	—	—	100.000	—	—	100.000	—	—
1.0–1.6 μm	100.000	—	—	100.000	—	—	100.000	—	—
1.6–2.0 μm	100.000	—	—	100.000	—	—	100.000	—	—
2.0–3.0 μm	100.000	—	—	100.000	—	—	100.000	—	—
	OPC Pair #2-Test A			OPC Pair #2-Test B			OPC Pair #2-COMBINED		
0.30–0.40 μm	99.998	99.997	100.000	99.999	99.998	100.000	99.999	99.998	99.999
0.40–0.50 μm	99.998	99.996	100.000	99.997	99.995	100.000	99.998	99.996	99.999
0.50–0.65 μm	100.000	—	—	99.998	99.995	100.000	99.999	99.997	100.000
0.65–0.80 μm	100.000	—	—	100.000	—	—	100.000	—	—
0.80–1.0 μm	100.000	—	—	99.992	99.975	100.000	99.996	99.987	100.000
1.0–1.6 μm	100.000	—	—	100.000	—	—	100.000	—	—
1.6–2.0 μm	100.000	—	—	100.000	—	—	100.000	—	—
2.0–3.0 μm	100.000	—	—	100.000	—	—	100.000	—	—

system integrity, as demonstrated by mean efficiencies as low as 96.156% and broad 95% confidence intervals. Again, as was noticed during Survey 2, high downstream particle counts in size ranges larger than 0.65 μm were noticed.

Because the evaluation of the Unit A-Floor showed that the system did not meet the strict USPS criteria, the system was completely dismantled to find possible leakage sites. An evaluation of the system design suggested a manufacturing defect in one or more of the metal duct seals, which could allow particle infiltration downstream of the filters. Such leakage, in turn, could result in contamination of the system downstream of the HEPA filters. Unit A-Floor was reconstructed, and enhanced measures taken to completely seal the system at all metal-to-metal joints. After reconstruction, Unit A-Floor was re-evaluated, and these data are also presented in Table III. The mean efficiency values all exceeded 99.989% and the lowest minimum 95% confidence limit was 99.986%, at the 0.3–0.4 μm size range. It was obvious that the modifications made to Unit A-Floor during the system reconstruction brought the system into compliance with the USPS acceptance criteria.

Finally, both matched pairs of OPCs (two matched instruments in Pair #1 and two in Pair #2, for a total of four) were run in Unit A4 to compare results. Both pairs operated simultaneously, yet independently. Although matched instruments were in each pair, Pair #1 did not match Pair #2. The only difference in this test sequence from previous evaluations involved switching the upstream and downstream OPCs in the middle of the test run. Table IV presents the data for both pairs (Pair #1 and Pair #2) of matched pairs. The data were evaluated in three segments: (1) Test A was the initial OPC configuration; (2) Test B was after switching the location of the upstream and downstream OPCs; and (3) the combined Test A and Test B data. The data from OPC Pair #1 were all within about 0.01% of each other. These data were extremely consistent and reproducible, having relatively narrow 95% confidence intervals. The same was true for the data from OPC Pair #2. The data from Pair #2 reveal that all values are within 0.025% of each other. Obtaining such consistent results shows the importance of choosing a pair of matched OPCs immediately prior to actual testing of VFS efficiency. Further, it demonstrates that switching locations of the upstream and downstream OPCs in the middle of the test is not required to further reduce instrument bias if a pair of instruments has been closely matched prior to testing.

CONCLUSIONS AND RECOMMENDATIONS

Based on the evaluation results detailed in this paper, the following conclusions can be made:

- The sampling strategy employed for these surveys effectively monitors total VFS performance in accordance with the strict acceptance criteria established by the USPS.
- Assuming that a closely matched pair of GRIMM OPCs is chosen (for this study, ±2.5% in total counts between 0.3 μm and 3.0 μm, and <1% difference in particle counts in the 0.30–0.40 μm size channel), there appears to be no need to switch the upstream and downstream OPCs during

testing to further reduce instrument-specific bias. This may or may not be the case with other OPCs.

- The methodology employed gives results that are statistically significant for a filtration efficiency of 99.97% or better for particle sizes between 0.3 μm and 3.0 μm using ambient aerosol. This may or may not be the case with other ventilation systems in other settings.
- This methodology distinguishes filtration units that are meeting or exceeded high-efficiency criteria from those that are in need of repair or replacement.
- The methodology employed during the USPS could be used by any workplace wishing to evaluate filtration systems, including high efficiency systems needing to achieve 99.97% or better filtration.

The following recommendations can be made:

- In the case of the USPS, where high levels of dust were created by mail processing, the ambient particulate levels were sufficient for use as the challenge. In other situations, however, it may be necessary to introduce additional particulate as the challenge.
- A maintenance program for the routine evaluation of the system filtration efficiency of all USPS VFS units should be implemented. As was demonstrated by our research at the USPS P&DCs, small leaks and perforations in the filter media can easily breach system integrity.
- Any workplace that depends on the performance of VFS units to prevent particulate exposures that can potentially cause illness should not rely on filtration media testing alone. As was clearly demonstrated at the USPS, other points in the system can adversely affect system filtration efficiency. It is, therefore, recommended that the method described here (or other similar method) be used to routinely verify total filtration system integrity.

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